

Substructure of the Nucleon in the Chiral Quark Model*

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Abstract

The spin and orbital angular momentum carried by different quark flavors in the nucleon are calculated in the SU(3) chiral quark model with symmetry-breaking. The similar calculation is also performed for other octet and decuplet baryons. Furthermore, the flavor and spin contents for charm and anti-charm quarks are predicted in the SU(4) symmetry breaking chiral quark model.

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I. Introduction

One of the important tasks in hadron physics is to reveal the internal structure of the nucleon. This includes the study of flavor, spin and orbital angular momentum shared by the quarks and gluons in the nucleon. These structures determine the basic properties of the nucleon: spin, magnetic moment, axial coupling constant, elastic form factors, and the deep inelastic structure functions. The polarized deep-inelastic scattering (DIS) data [1,2] indicate that the quark spin only contributes about one third of the nucleon spin or even less. A natural and interesting question is: where is the *missing* spin? Intuitively, and also from quantum chromodynamics (QCD) [3], the nucleon spin can be decomposed into the quark and gluon contributions

$$\frac{1}{2} = \langle J_z \rangle_{q+\bar{q}} + \langle J_z \rangle_G = \frac{1}{2}\Delta\Sigma + \langle L_z \rangle_{q+\bar{q}} + \langle J_z \rangle_G \quad (1)$$

where $\Delta\Sigma = \sum_q [\Delta q + \Delta \bar{q}]$ and $\langle L_z \rangle_{q+\bar{q}}$ are the total helicity and orbital angular momentum carried by quarks and antiquarks. $\langle J_z \rangle_G$ is the gluon angular momentum. The smallness of $\frac{1}{2}\Delta\Sigma$ implies that the missing part should be contributed either by the quark orbital motion or the gluon angular momentum. Most recently, it has been shown that $\langle J_z \rangle_{q+\bar{q}}$ might be measured in the deep virtual Compton scattering process [4], and one may then

^{1*} Plenary talk presented at the Circum-Pan-Pacific RIKEN Symposium on ‘High Energy Spin Physics’, RIKEN, Wako, Japan, November 3-6, 1999.

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obtain the quark orbital angular momentum from the difference $\langle J_z \rangle_{q+\bar{q}} - \frac{1}{2}\Delta\Sigma$. Hence the study of the quark spin and orbital angular momentum are important and interesting both experimentally and theoretically.

In the naive quark model, $\langle L_z \rangle_{q+\bar{q}} = 0$ and $\langle L_z \rangle_G = 0$. In the bag model [5], $\frac{1}{2}\Delta\Sigma \simeq 0.39$, and $\langle L_z \rangle_q \simeq 0.11$, while in the Skyrme model [6], $\Delta G = \Delta\Sigma = 0$, and $\langle L_z \rangle = \frac{1}{2}$. Most recently Casu and Sehgal [7] show that to fit the baryon magnetic moments and polarized DIS data, a large collective orbital angular momentum $\langle L_z \rangle$, which contributes almost 80% of nucleon spin, is needed. Hence the question of how much of the nucleon spin is coming from the quark orbital motion remains.

II. SU(3) Chiral Quark Model

(a) Basic Assumptions

The effective interaction Lagrangian for SU(3) chiral quark model [8] is

$$L_I = g_8 \bar{q} \begin{pmatrix} G_u^0 & \pi^+ & \sqrt{\epsilon} K^+ \\ \pi^- & G_d^0 & \sqrt{\epsilon} K^0 \\ \sqrt{\epsilon} K^- & \sqrt{\epsilon} \bar{K}^0 & G_s^0 \end{pmatrix} q, \quad (2a)$$

where $G_{u(d)}^0$ and GB_s^0 are defined as

$$G_{u(d)}^0 = +(-)\pi^0/\sqrt{2} + \sqrt{\epsilon_\eta}\eta^0/\sqrt{6} + \zeta'\eta'^0/\sqrt{3}, \quad G_s^0 = -\sqrt{\epsilon_\eta}\eta^0/\sqrt{6} + \zeta'\eta'^0/\sqrt{3}. \quad (2b)$$

The breaking effects are explicitly included. $a \equiv |g_8|^2$ denotes the transition probability of chiral fluctuation or splitting $u(d) \rightarrow d(u) + \pi^{+(-)}$, and ϵa denotes the probability of $u(d) \rightarrow s + K^{-(0)}$. Similar definitions are used for $\epsilon_\eta a$ and $\zeta'^2 a$. If the breaking is dominated by mass suppression effect, one reasonably expects $0 \leq \zeta'^2 a < \epsilon_\eta a \simeq \epsilon a \leq a$.

The basic *assumptions* of the chiral quark model are: (i) the quark flavor, spin and orbital contents of the nucleon are determined by its valence quark structure and all possible chiral fluctuations, and probabilities of these fluctuations depend on the interaction Lagrangian (2), (ii) the coupling between the quark and Goldstone boson is rather weak, one can treat the fluctuation $q \rightarrow q' + \text{GB}$ as a small perturbation ($a \sim 0.10 - 0.15$) and the contributions from the higher order fluctuations can be neglected, and (iii) quark spin-flip interaction dominates the splitting process $q \rightarrow q' + \text{GB}$. This can be related to the picture given by the instanton model [9], hence the spin-nonflip interaction is suppressed.

Based upon the assumptions, the quark *flips* its spin and changes (or maintains) its flavor by emitting a charged (or neutral) Goldstone boson. The light quark sea asymmetry $\bar{u} < \bar{d}$ is attributed to the existing *flavor asymmetry* of the valence quark numbers (two valence u -quarks and one valence d -quark) in the proton. On the other hand, the quark spin reduction is due to the *spin dilution* in the chiral splitting processes. Furthermore, the quark spin component changes one unit of angular momentum, $(s_z)_f - (s_z)_i = +1$ or -1 , due to spin-flip in the fluctuation with GB emission. The angular momentum conservation requires the *same* amount change of the orbital angular momentum but with *opposite sign*, i.e. $(L_z)_f - (L_z)_i = -1$ or $+1$. This *induced* orbital motion is distributed among the quarks and antiquarks, and compensates the spin reduction in the chiral splitting.

(b) Quark Spin Contents in the Nucleon

The spin-weighted quark contents are

$$\Delta u^p = \frac{4}{5}\Delta_3 - a, \quad \Delta d^p = -\frac{1}{5}\Delta_3 - a, \quad \Delta s^p = -\epsilon a, \quad (3a)$$

where $\Delta_3 = \frac{5}{3}[1 - a(\epsilon + 2f)]$ and $f \equiv \frac{1}{2} + \frac{\epsilon}{6} + \frac{\zeta'^2}{3}$. The total quark spin content in the proton is

$$\frac{1}{2}\Delta\Sigma^p = \frac{1}{2}(\Delta u^p + \Delta d^p + \Delta s^p) = \frac{1}{2} - a(1 + \epsilon + f) \equiv \frac{1}{2} - a\xi_1 \quad (3b)$$

where the notation $\xi_1 \equiv 1 + \epsilon + f$ is defined. A special feature of the chiral quark model is that *all the spin-weighted antiquark contents are zero*

$$\Delta\bar{q} = 0. \quad (3c)$$

Hence $(\Delta q)_{sea} \neq \Delta\bar{q}$, which differs from the predictions of the sea quark and antiquark pair produced by a gluon (see discussion in [10]).

(c) Quark Orbital Momentum in the Nucleon

The orbital angular momentum produced in the splitting $q_{\uparrow} \rightarrow q'_{\downarrow} + \text{GB}$ is shared by the recoil quark (q') and the Goldstone boson (GB). Defining 2κ as the fraction of the orbital angular momentum shared by the GB, then the fraction shared by the recoil quark is $1 - 2\kappa$. We assume the fraction of 2κ is equally shared by the quark and antiquark in the GB and call κ the *partition factor* which satisfies $0 < \kappa < 1/2$. For $\kappa = 1/3$, the three particles – the recoil quark, quark and antiquark in the GB equally share the induced orbital angular momentum. For the proton, we obtain

$$\langle L_z \rangle_q^p \equiv \langle L_z \rangle_{u+d+s}^p = (1 - \kappa)\xi_1 a \quad (4a)$$

$$\langle L_z \rangle_{\bar{q}}^p \equiv \langle L_z \rangle_{\bar{u}+\bar{d}+\bar{s}}^p = \kappa\xi_1 a \quad (4b)$$

and

$$\langle L_z \rangle_{q+\bar{q}}^p \equiv \langle L_z \rangle_q^p + \langle L_z \rangle_{\bar{q}}^p = \xi_1 a \quad (4c)$$

The orbital angular momentum of each quark flavor may depend on the partition factor κ , but the total orbital angular momentum (4c) is independent of κ . Furthermore, the amount $\xi_1 a$ is just the same as the total spin reduction in (3b), and the sum of (4c) and (3b) gives

$$\langle J_z \rangle_{q+\bar{q}}^p = \frac{1}{2}\Delta\Sigma_{q+\bar{q}}^p + \langle L_z \rangle_{q+\bar{q}}^p = \frac{1}{2} \quad (4d)$$

In the chiral fluctuations, the missing part of the quark spin is *transferred* into the orbital motion of quarks and antiquarks. The amount of quark spin reduction $a(1 + \epsilon + f)$ in (3b) is canceled by the equal amount increase of the quark orbital angular momentum in (4c), and the total angular momentum of nucleon is unchanged.

(d) Paramters

The model parameters are determined by three inputs, $\Delta u - \Delta d = 1.26$, $\Delta u + \Delta d - 2\Delta s = 0.60$, and $\bar{d} - \bar{u} = 0.143$. The result is: $a = 0.145$, $\epsilon = 0.46$, and $\zeta'^2 = 0.10$. The orbital angular momenta shared by different quark flavors are listed in Table I. We plot the orbital angular momenta carried by quarks and antiquarks in the proton as function of κ in Fig.1. Using the parameter set given above, $\langle L_z \rangle_{q+\bar{q}}^p \simeq 0.30$, i.e. nearly 60% of the proton spin is coming from the orbital motion of quarks and antiquarks, and 40% is contributed by the quark and antiquark spins. Comparison of our result with other models is given in Fig.2.

Extension to other baryons and application to the baryon magnetic moments were discussed in [8]. It has been shown that although the chiral model result of the magnetic

moments seems to be better than the nonrelativistic quark model result, there is no significant difference between them. This is because the positive orbital contribution to the magnetic moment cancels in part the negative contribution given by the quark spin reduction. This cancellation was also discussed in [11]. Hence the magnetic moment might not be a good observable to manifest the quark orbital contribution.

II. SU(4) Chiral Quark Model

The effective interaction Lagrangian in SU(4) case is

$$L_I = g_{15} \bar{q} \begin{pmatrix} G_u^0 & \pi^+ & \sqrt{\epsilon} K^+ & \sqrt{\epsilon_c} \bar{D}^0 \\ \pi^- & G_d^0 & \sqrt{\epsilon} K^0 & \sqrt{\epsilon_c} D^- \\ \sqrt{\epsilon} K^- & \sqrt{\epsilon} \bar{K}^0 & G_s^0 & \sqrt{\epsilon_c} D_s^- \\ \sqrt{\epsilon_c} D^0 & \sqrt{\epsilon_c} D^+ & \sqrt{\epsilon_c} D_s^+ & G_c^0 \end{pmatrix} q, \quad (6)$$

where $G_{u(d)}^0$ and G_s^0 are defined similarly as in (2b), but with additional ϵ_c term, and $G_c^0 = -\zeta' \frac{\sqrt{3}\eta^0}{4} + \sqrt{\epsilon_c} \frac{3\eta_c}{4}$, with $\eta_c = (c\bar{c})$.

In the SU(4) chiral quark model, the charm and anticharm quarks are produced nonperturbatively, and they are ‘*intrinsic*’. The intrinsic charm helicity Δc is nonzero and definitely negative. To estimate the size of Δc and other intrinsic charm contributions, we use the same parameter set ($a = 0.145$, $\epsilon \simeq \epsilon_\eta = 0.46$, $\zeta'^2 = 0.10$) given in the SU(3) case, and leave ϵ_c as a variable, then other quark flavor and helicity contents can be expressed as functions of ϵ_c . We found that $\epsilon_c \simeq 0.1 - 0.3$ satisfactorily describes the data. Our model results, data, and theoretical predictions from other approaches are listed in Table II and Table III respectively. Several remarks are in order: (1) our result, $2\bar{c}/\Sigma(q + \bar{q}) \simeq 3.7\%$, agrees with that given in [12] and the earlier number given in [13]. But the result given in [14] is much smaller (0.5%) than ours. (2) our prediction $\Delta c = -0.029 \pm 0.015$ is very close to the result $\Delta c = -0.020 \pm 0.005$ given in the instanton QCD vacuum model [15]. However the size of Δc given in [16] is about two order of magnitude smaller than ours. (3) We plot the ratio $\Delta c/\Delta \Sigma$ as function of ϵ_c in Fig.3. Our result $\Delta c/\Delta \Sigma \simeq 0.084 \pm 0.046$ agrees well with the prediction given in [17] and is also not inconsistent with the result given in [15].

To summarize, the chiral quark model with a few parameters can well explain many existing data of the nucleon properties: (1) strong flavor asymmetry of light antiquark sea: $\bar{d} > \bar{u}$, (2) nonzero strange quark content, $\langle \bar{s}s \rangle \neq 0$, (3) sum of quark spins is small, $\langle s_z \rangle_{q+\bar{q}} \simeq 0.1 - 0.2$, (4) sea antiquarks are not polarized: $\Delta \bar{q} \simeq 0$ ($q = u, d, \dots$), (5) polarizations of the sea quarks are nonzero and negative, $\Delta q_{sea} < 0$, (6) the orbital angular momentum of the sea quark is parallel to the proton spin, and (7) the SU(4) chiral quark model predicts a small amount of intrinsic charm and a negative Δc in the proton. (1)-(4) are consistent with data, and (5)-(7) could be tested by future experiments.

Acknowledgments

The author would like to thank S. Brodsky, P. K. Kabir and H. J. Weber for useful comments and suggestions. This work was supported in part by the U.S. DOE Grant No. DE-FG02-96ER-40950, the Institute of Nuclear and Particle Physics, University of Virginia, and the Commonwealth of Virginia.

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TABLES

TABLE I. Quark spin and orbital angular momentum in the proton in different models.

Quantity	Data [2]	This paper			CS [7]	NQM
		$\kappa = 1/4$	$\kappa = 1/3$	$\kappa = 3/8$		
$\langle L_z \rangle_u^p$	—	0.115	0.130	0.138	—	0
$\langle L_z \rangle_d^p$	—	0.073	0.043	0.027	—	0
$\langle L_z \rangle_s^p$	—	0.038	0.028	0.023	—	0
$\langle L_z \rangle_{\bar{u}}^p$	—	−0.003	−0.003	−0.003	—	0
$\langle L_z \rangle_{\bar{d}}^p$	—	0.057	0.076	0.085	—	0
$\langle L_z \rangle_{\bar{s}}^p$	—	0.021	0.028	0.031	—	0
$\langle L_z \rangle_{q+\bar{q}}^p$	—	0.30	0.30	0.30	0.39	0
Δu^p	0.85 ± 0.05		0.86		0.78	4/3
Δd^p	-0.41 ± 0.05		−0.40		−0.34	−1/3
Δs^p	-0.07 ± 0.05		−0.07		−0.14	0
$\frac{1}{2}\Delta\Sigma^p$	0.19 ± 0.06		0.20		0.08	1/2

TABLE II. Quark flavor observables

Quantity	Data	SU(3)	SU(4)
$\bar{d} - \bar{u}$	0.147 ± 0.039 0.110 ± 0.018	0.147	0.120
\bar{u}/\bar{d}	$\frac{[\bar{u}(x)]}{[\bar{d}(x)]}_{0.1 < x < 0.2} = 0.67 \pm 0.06$ $\frac{[\bar{u}(x)]}{[\bar{d}(x)]}_{x=0.18} = 0.51 \pm 0.06$	0.65	0.69
$2\bar{s}/(\bar{u} + \bar{d})$	$\frac{\langle 2x\bar{s}(x) \rangle}{\langle x(\bar{u}(x) + \bar{d}(x)) \rangle} = 0.477 \pm 0.051$	0.69	0.69
$2\bar{c}/(\bar{u} + \bar{d})$	—	0	0.28 ± 0.14
$2\bar{s}/(u + d)$	$\frac{\langle 2x\bar{s}(x) \rangle}{\langle x(u(x) + d(x)) \rangle} = 0.099 \pm 0.009$	0.128	0.120
$2\bar{c}/(u + d)$	—	0	0.05 ± 0.02
$f_s \equiv 2\bar{s}/\sum(q + \bar{q})$	0.10 ± 0.06 0.15 ± 0.03 $\frac{\langle 2x\bar{s}(x) \rangle}{\sum \langle x(q(x) + \bar{q}(x)) \rangle} = 0.076 \pm 0.022$	0.10	0.09
$f_c \equiv 2\bar{c}/\sum(q + \bar{q})$	0.03 [12] 0.02 [13] 0.005 [14]	0	0.037 ± 0.015
$\sum \bar{q}/\sum q$	$\frac{\sum \langle x\bar{q}(x) \rangle}{\sum \langle xq(x) \rangle} = 0.245 \pm 0.005$	0.235	0.246
f_3/f_8	0.23 ± 0.05	0.21	0.22

TABLE III. Quark spin observables

Quantity	Data	SU(3)	SU(4)
Δu	0.85 ± 0.04	0.86	0.83
Δd	-0.41 ± 0.04	-0.40	-0.39
Δs	-0.07 ± 0.04	-0.07	-0.07
Δc	-0.020 ± 0.004 [15] $-5 \cdot 10^{-4}$ [16]	0	-0.029 ± 0.015
$\Delta \bar{u}, \Delta \bar{d}$	-0.02 ± 0.11	0	0
$\Delta \bar{s}, \Delta \bar{c}$	—	0	0
$\Delta c / \Delta \Sigma$	-0.08 ± 0.01 [17] -0.033 [15]	0	-0.084 ± 0.046
$\Delta c / c$	—	—	-0.314
Γ_1^p	0.136 ± 0.016	0.133	0.133
Γ_1^n	-0.036 ± 0.007	-0.037	-0.034
Δ_3	1.2573 ± 0.0028	1.26	1.259
Δ_8	0.579 ± 0.025	0.60	0.578

FIGURES

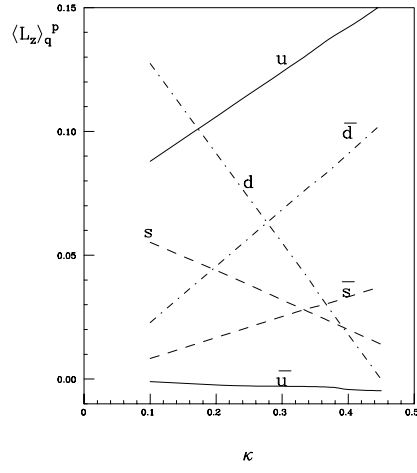


FIG. 1. Quark or antiquark orbital angular momentum $\langle L_z \rangle_{q,\bar{q}}$ in the proton as function of κ .

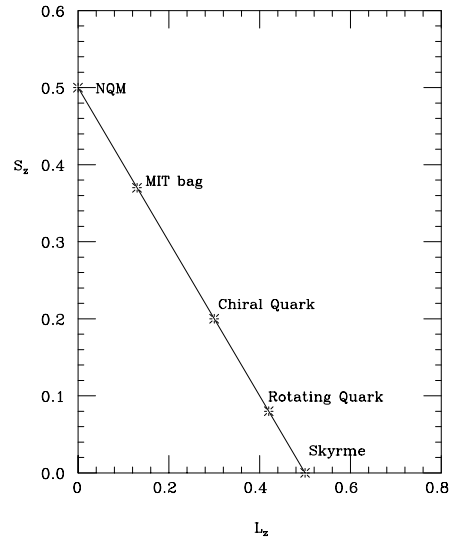


FIG. 2. Quark spin and orbital angular momentum in the nucleon in different models.

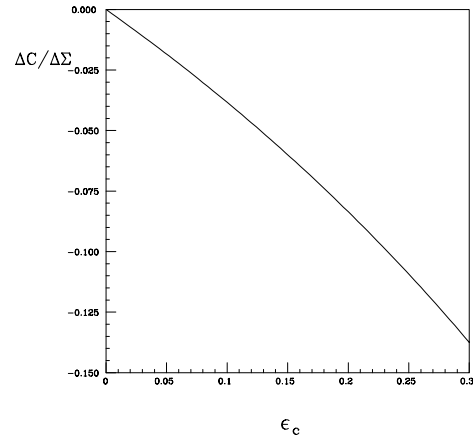


FIG. 3. Intrinsic charm quark polarization in the proton as function of ϵ_c .